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ADVANCED ARRAY RESEARCH

Quarterly Report No. 4

15 September 1967 through 14 December 1967

George Hair, Program Manager
Area Code 214, 238-3473

TEXAS INSTRUMENTS INCORPORATED
Science Services Division
P. O. Box 5621
Dallas, Texas 75222

Contract No. F33657-67-C-0708-P001
Beginning 15 December 1966
Ending 14 December 1967

Prepared for

AIR FORCE TECHNICAL APPLICATIONS CENTER
Washington, D. C. 20333

Sponsored by

ADVANCED RESEARCH PROJECTS AGENCY
Nuclear Test Detection Office
ARPA Order No. 624
AFTAC Project No. VT/7701

5 January 1968

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TEXAS INSTRUMENTS
INCORPORATED

SCIENCE SERVICES DIVISION

5 January 1968

Air Force Technical Applications Center
VELA Seismological Center
Headquarters, USAF
300 N. Washington Street
Alexandria, Virginia 22314

Attention: Captain Carroll F. Lam

Subject: Quarterly Report No. 4 for period 15 September 1967 through 14 December 1967

Identification:
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Amount of Contract: $625,500
Contract Expiration Date: 14 December 1967
Project Manager: George Hair
Area Code 214
238-3473

WORK PROGRESS

Progress during the fourth quarter is summarized in this report by principal tasks. Several special reports are described which along with the annual technical report will be published before 14 February 1968. It is planned that the detailed quantitative results of all research will be reported by way of special reports. The annual report will summarize qualitatively, with a minimum of quantitative results, all research conducted during the year and will fully discuss the motivation, objectives, techniques, results and conclusions for each area of investigation.

Task A

> Using an ensemble of seismic array network data to be furnished by AFTAC, investigate bodywave noise on a coherent worldwide basis. Investigate interarray equalization problems. Study methods of combining the subarray output for network signal extraction. Investigate the capabilities of a worldwide network for resolving events closely spaced in time and space.

Network noise analysis data processing is completed, interpretation of results essentially completed, and two special reports are being prepared to present the results of the noise studies. The first of these, Special Report No. 6, "A Study of Spatially-Organized Short-Period Network Noise", summarizes a study of the short-period network noise structure through analysis of station array data. Included are power spectra from all available network stations for five noise samples. Two of these samples, both reflecting heavy storm activity in the northern latitudes, are further studied using high-resolution f-k spectra computed for five array stations. A comparative study of various techniques for computing f-k spectra is also presented. This report summarizes network and station descriptions, including station array characteristics.

Station f-k spectra are presented every 0.2 Hz from 0.2 Hz to 1.0 Hz (TFO), 1.4 Hz (OONW, GGGR, NPNT), and 2.0 Hz (CPO), with unit cell sizes determining maximum frequencies. Dominant coherent energy appears highly directional and largely correlated with meteorological and windwave charts. Some apparently time-stationary energy peaks are also observed at most stations, and are probably culturally-generated. Dominant spectral peaks at TFO are generally bodywave; at CPO, NPNT, GGGR, and OONW, surface-mode. A few bodywave peaks seen at OONW and NPNT also appear related to storm activity.

Although intense storm centers are detected at several stations, amplitude, frequency and propagation modes all vary from station to station. Therefore, negligible coherence is expected at the network level, and network-level multichannel processing to suppress this noise energy does not appear practical.

The second report, Special Report No. 8, "Network Noise Dissection Studies", summarizes efforts to partition the network noise field into high and low velocity components. Presented are results of various approaches to this problem, such as adaptive filtering, velocity filtering, and k-line spectral analysis of crossarray data. Also presented are results of spectral analysis of long-period vertical component data. Generally, no long-period coherence was observed, except for weak (.05 - .15) coherence measured between various station pairs on the same continental mass in the frequency range between .03 and .3 Hz. While demonstrated coherence at such extreme ranges is significant, the level of coherence is apparently much too low for effective use in multichannel processing.

An attempt to form broadband spectral estimates of the network noise field by joining long-period and short-period power spectra is also presented. The report will also summarize the results of an evaluation of a technique for obtaining worldwide f-k spectra using network station outputs as components of a worldwide array.

Work on the network signal characteristics study has been completed for two events. These two events have been processed at the network level using various signal enhancement techniques, and the results have been analyzed by computing signal-to-noise ratios, broadband power spectra, and by visual analysis of the processed traces.

Processing techniques investigated have included simple beam-steer, signal-to-noise weighted beam-steer, Levinson equalized beam-steer, and signal-to-noise weighted Levinson equalized beam-steer. Also, the first event analyzed, Kamchatka #1, was processed using both broadband and band-limited data; however, band-limit filtering was found to be essential for network processing, and thus was included in all processing of the Kurile #2 event.

In general, results of this study have shown that signal-to-noise weighted beam-steering of band-limited data is the best processing technique for the events studied, i.e., it produces the greatest increase in signal-to-noise ratio in the peak signal frequency band.

In the depth phase study, processing of the Kamchatka event and three Kurile Island events has been completed. The technique investigated for detecting depth phases requires the squaring-and-integration of P-30 correlations - the crosscorrelation between the first few seconds of the P phase and the entire P coda.

This study demonstrated enhancement of depth phases on several events with a fair agreement between reported and observed arrival times. Although the small number of available events severely limited this study, the results were encouraging since the technique investigated did show the ability of a seismic network to attenuate noise and scattered signal energy while enhancing depth phases.

Results of the study of the capability of an 8-station network to separate two time-overlapping events, synthesized to be 1° apart in epicenter, through beam-steering followed by squaring-and-integration have been analyzed. It is demonstrated that even a rather limited network can detect and separate multiple events having an epicenter separation of less than 1° when the difference in event magnitude does not exceed 0.5.

Results of the signal characteristics, depth phase enhancement, and signal separation studies are currently being prepared for publication as Special Report No. 7.

Task B

Continue investigations of multi-element system studies to determine possible new combinations of sensors for noise reduction. Study methods of specifying, for given noise fields, the optimum multisensor system for noise reduction with the desired result a set of guidelines for array design. These guidelines should include, but not be limited to, the type of sensors required and, for an array, the size and geometry, subject to the constraints of practicability.

Formulas giving the crosspower between two seismic sensors corresponding to an assumed f-k space signal or noise model have been obtained. Salient features of the problem treated are the following.

- The propagating medium is assumed to be a horizontally stratified series of homogeneous layers overlying a homogeneous halfspace
- An isotropic or a directional f-k space model for compressional or Rayleigh wave vertical displacement power is the assumed input
- The development covers vertical and/or horizontal displacement sensors which are separated both vertically and azimuthally

The solution of this problem is significant in that it can readily be extended to encompass other situations of interest. To illustrate this the modifications necessary to handle Love wave propagation and measurement with strain sensors have been made. A special report presenting these results is in publication.

A theoretical study of the relative performances of beam-steering and MCF applied to long-period arrays was performed. Here the signal was considered to be a fundamental mode Rayleigh wave coming from a specific direction. The noise field consisted predominantly of isotropic fundamental mode Rayleigh waves and a small amount of random noise. Array signal-to-noise improvements for a seven-element and a nineteen-element array of vertical seismometers, both on hexagonal grids, were computed. As expected, the MCF was superior to the beam-steer by varying amounts ranging up to 5 db. This work, however, provided an additional interesting result. Signal-to-noise improvement of either type of processor when plotted as a function of frequency has a series of maxima and minima. The reason for this behavior is quite clear. At any given frequency the array response is peaked at the wavenumber of the signal power.. Aliases of this wavenumber are also regions of high response and at certain frequencies some isotropic noise power falls in these regions. At such frequencies performance minima occur.

The predictability of this behavior suggests that one might imply with good accuracy the performance of a proposed array in the more probable case where the noise is not isotropic. If signals from a specific direction are to be monitored and if the nature of the noise field is known, then consideration of these aliasing effects would assist in choosing the spacing and orientation of the array. These results will be presented in a special report.

Processing of the horizontal seismometer data from WMO has been completed. The goal of this work was to experimentally investigate the value of horizontal seismometers for compressional wave signal extraction. Two concentric rings of horizontal seismometers were used to predict the noise on a central vertical seismometer. Multichannel filters were designed using both conventional techniques and an adaptive algorithm. Results in the two cases were similar. An average SNR improvement of about 3 db was obtained. At frequencies below 1 Hz, this performance is expected since the bodywave noise level is slightly higher than the surface wave noise level. At frequencies above 1 Hz, however, greater SNR improvement was expected. It is possible that a relatively higher random noise level prevented achieving better performance. Noticeable lack of uniformity in the seismic noise traces suggests this possibility. Theoretical results indicate that random noise is a more severe problem for arrays of this type than it is for a similar array of vertical seismometers. Details of this work will be presented in a special report now in preparation.

Tasks C and D

> Theoretically investigate methods of implementing continuously adaptive systems for application to time-varying noise fields and postdetection processing. Any system that can be simulated off-line should be evaluated using suitably characteristic data. Investigate the effects and methods of reducing locally generated noise. The effects of such non-plane wave fields on multichannel filter design should be evaluated.

Processing to determine the effect of adaptive filtering on over-sampled data has been completed on three sets of two channel data. The channels are generated to be independent and have uniform power out to 5%, 25%, and 100% of the folding frequency. Mean square error curves versus k_s in predicting one channel with an adaptive filter operating on the other were computed to illustrate the degree of false improvement due to oversampling.

A composite of five noise samples from a short-period surface array was chosen to compare adaptive maximum likelihood filters to Wiener filters. The Wiener filters were designed from the stacked correlations, infinite velocity signal model, SNR = 4 with gain variability, and applied to the first 1000 points of each of the five noise samples.

The maximum likelihood filters were adaptively designed by obtaining a starting set of filters from the first noise sample using a large value of k_s. The first half of each noise sample was then processed in the order 1 to 5 using a smaller k_s, and finally the last half of each noise sample was processed in the order 5 to 1 with an extremely small value of k_s. These adaptively designed filters were then fixed and applied to the first 1000 points of each noise sample. For comparison, a straight stack and large k_s adaptive outputs were also computed.

Spectra of the error traces indicate that the Wiener filter is better (2 db) at .5 Hz with a crossover at approximately 1 Hz and the adaptively designed maximum likelihood filter performs better (up to 15 db) over the band 2 to 5 Hz. The fixed adaptive and large k_s adaptive performed alike except for frequencies above 2 Hz where an improvement of up to 10 db implies a consistent high frequency time varying component. The results will be included in a special report on adaptive processing now in preparation.

<u>Task E</u>

Continue studies of the instrumental equalization problem. Apply any new techniques available for studying instrumental equalization and evaluate the effectiveness of such techniques.

1. Group Coherence Study

If an array of seismometers is partitioned into two groups and a set of multichannel filters is designed for each group such that the coherence between the two MCF outputs is a maximum, this coherence is known as the Group Coherence. The wavenumber response of both MCF sets should tend to peak and be highly similar in regions where the wavenumber power spectrum is a maximum. The wavenumber response of the difference between the two MCF sets should have a small power response at the wavenumber peaks. One would think that highly coherent energy such as that generated by storms or earthquakes would appear as regions of low power in the wavenumber response of the difference.

The object of this study was to investigate

- Whether the wavenumber response of the difference may be used as a tool for detecting and isolating regions of highly coherent energy
- Whether the multichannel filter weights may be used for determining the amplitude and phase response inequalizations of seismometers in the array

The following data were used for this study

- The TFO long noise sample
- A model closely approximating the TFO long noise sample
- A model closely approximating the TFO long noise sample with 1% white noise added

High coherence was obtained for several MCF sets. However, the technique lacks the wavenumber resolution that is needed for isolating highly coherent regions. Thus, the technique is inadequate for detecting seismometer inequalizations, which are second order effects.

Conclusions drawn from these experiments are

- The technique is good for measuring similarity between the outputs of the two partitioned sets and the multichannel filters are useful if the object is to generate the maximum coherent MCF outputs
- The technique is of little value in either isolating regions of high power in wavenumber space or in determining seismometer inequalizations

FINANCIAL STATUS

The financial status of the project as of 31 November 1967 is summarized on the Cost Planning and Appraisal Chart submitted under separate cover on 20 December 1967. No significant total variance from the original cost estimate is anticipated.

Very truly yours,

TEXAS INSTRUMENTS INCORPORATED

George Hair

George Hair
Program Manager

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13. ABSTRACT

Progress during the fourth quarter and plans for several special reports and the annual report are presented. Tasks reported are: network studies, multisensor arrays, continuously adaptive filtering, and group coherence.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Bodywave noise						
High-resolution techniques						
Continuously adaptive systems						
Network signal extraction						
Phase extraction						
Crosspower/crosscorrelation matrix program						
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